DEPARTMENT OF COMMERCE
BUREAU OF STANDARDS
George K. Burgess, Director

USE AND TESTING OF SPHYGMOMANOMETERS

By J. L. Wilson, H. N. Eaton, and H. B. Henrickson

TECHNOLOGIC PAPERS OF THE BUREAU OF STANDARDS, No. 352

DEPARTMENT OF COMMERCE
BUREAU OF STANDARDS
George K. Burgess, Director

TECHNOLOGIC PAPERS OF THE BUREAU OF STANDARDS, No. 352
[Part of Vol. 21]

USE AND TESTING OF SPHYGMOMANOMETERS

BY

J. L. WILSON, Assistant Physicist
H. N. EATON, Engineer
H. B. HENRICKSON, Assistant Physicist
Bureau of Standards

August 30, 1927

PRICE, 20 CENTS
$1.25 PER VOLUME ON SUBSCRIPTION
Sold only by the Superintendent of Documents, U. S. Government Printing Office
Washington, D. C.

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON
1927

USE AND TESTING OF SPHYGMOMANOMETERS

By J. L. Wilson, H. N. Eaton, and H. B. Henrickson

ABSTRACT

This publication contains a brief discussion of the characteristics of blood pressure in the human body, a description of the methods and instruments used in measuring arterial blood pressure, and résumé of results obtained in an investigation of the performance of the pressure indicators used in blood-pressure measurement. As a result of this investigation, standard tests were formulated and tolerances for accuracy of performance were established for use by the Bureau of Standards in testing blood-pressure gauges. The recommendations of leading medical authorities on blood pressure in the United States were given careful consideration in establishing the tolerances.

CONTENTS

I. INTRODUCTION

During the World War blood-pressure instruments were used extensively, not only in general practice but also in the examination of military and naval aviators, since the greatest importance is attached to the action of the heart at high altitudes. In 1917, at the request of the Surgeon General of the Army, an investigation of

several types of sphygmomanometers was undertaken by the aeronautic instruments section of the Bureau of Standards. Later this bureau was requested by several manufacturers to recommend limits of error which should not be exceeded by the gauges when subjected to specified tests. This resulted in a thorough investigation of the pressure indicators used with blood-pressure apparatus. Opinions were requested from the heads of hospitals and medical schools and from physiologists as to the required accuracy in blood-pressure measurment. The information received from these authorities was given due weight in specifying the tolerances. Throughout this investigation the most cordial cooperation has been rendered this bureau by physicians and manufacturers, and occasion is here taken to acknowledge this assistance.

In 1921 an informal report of this investigation was issued in the form of a circular of the aeronautic instruments section of the Bureau of Standards. Since that time many blood-pressure gauges have been sent to this bureau by physicians, manufacturers, and various Government departments for examination. The present paper includes the results of tests on these instruments as well as those tested in the previous investigation. Since this publication has been prepared for the use of both manufacturers and physicians, it has been necessary to include material that may seem unnecessarily elementary to one or the other.

II. BLOOD-PRESSURE MEASUREMENT

1. CHARACTERISTICS OF BLOOD PRESSURE

A knowledge of some of the simpler characteristics of blood pressure is essential to an understanding of the technique of its measurement and, consequently, of the conditions to which blood-pressure gauges are subjected in their use. The following discussion does not pretend to be an exhaustive treatment but sets forth the simpler aspects of the subject.

The human circulatory system consists of an intermittently working pump (the heart) forcing the blood through a system of subdividing elastic tubes (the arteries) to interlacing capillaries, and from these through another system of tubes (the veins) back to the pump. The work of the pump is expended in overcoming the peripheral friction of the tubes, by far the greatest part of which occurs in the arterioles and capillaries. Since the heart, like any simple pump, does not force out a steady stream of blood, a wave of increased pressure, which constitutes the pulse, starts through the system at each beat; but because of the elasticity of the arterial system, whereby its volume can increase with increased pressure, and because of the frictional resistance offered by the walls, especially those of the capillaries, the amplitude of the wave decreases as it

gets farther from the heart until the pressure on the other side of the capillaries, in the venous system, is substantially free from fluctuations due to the arterial wave.

The pressure at any point of the body is constantly varying rhythmically in several overlapping cycles. The first or cardiac cycle, the most important and having the greatest amplitude, is caused by the beat of the heart. The second or respiratory cycle, with an amplitude of 5 to 10 millimeters, is caused by the complicated effect of respiration which, by changing the intrathoracic and intraabdominal pressures, acts as an accessory pump with a much slower stroke. A third cycle, consisting of the so-called "Traube-Herring" waves of small amplitude, extends over several respiratory cycles. Its cause is unknown. In addition to these variations, the normal blood pressure is subject to many additional changes, often considerable, so that at least any single determination of the blood pressure, even if accurately made, is only an approximation to the average.

In ordinary clinical measurements the pressures at only two phases of the cardiac cycle are generally considered—the diastolic and the systolic pressures.

The diastolic pressure is the lowest pressure in the cardiac cycle. It occurs during the last of diastole, which extends from the end of one contraction of the heart to the beginning of the next and may be considered a measure of the peripheral resistance of the vascular system plus the factor due to the elastic contraction, or tone, of the walls of the vessels. This pressure varies, sometimes considerably, from diastole to diastole.

The systolic pressure, sometimes called the maximal pressure, is the greatest that occurs in the artery during systole; in other words, at the height of the contraction of the heart. It depends, as does the diastolic pressure, on the many factors influencing the general blood pressure.

The pulse pressure is simply the difference between the diastolic and the systolic pressures.

It does not fall within the purpose of this paper to discuss the range of normal blood pressure in any detail. What is normal in any case must be decided with the aid of the whole clinical picture of that case, and any arbitrary standards are very misleading. Particularly in old age is it hard to establish normal limits, since pathological conditions are then so usual that their absence might be considered abnormal.

Normal systolic pressures, determined in the customary way, can be said to range from 90 to 140 millimeters of mercury (3),[1] although

[1] The figures given in parentheses here and throughout the text relate to the numbers under heading "References," given at the end of this paper.

these limits can by no means be set as absolute. The majority of normal systolic pressures are between 110 and 130. Normal diastolic pressures are usually found to be between 60 and 100 millimeters of mercury, and the large majority occur between 70 and 90. In general, it can be stated that the diastolic pressure is normally about two-thirds of the systolic pressure.

2. USUAL METHOD OF MEASURING BLOOD PRESSURE (1, 2)

All measurements of blood pressure in man are made without direct connection with a blood vessel. Pressure is applied over some artery, usually the brachial artery above the elbow, until it is so compressed that the flow of blood is stopped entirely or persists only during a part of the cycle. When the compressing pressure is adjusted until the artery is closed except at the very peak of the arterial-pressure cycle, the external pressure is assumed to be equal to the systolic pressure; when it is adjusted until the artery is closed only at the lowest part of the arterial-pressure cycle, the external pressure is assumed to be equal to the diastolic pressure. The difficulty of recognizing when the two above-mentioned conditions exist is responsible for much of the uncertainty which has been associated with blood-pressure measurments. Different criteria have been developed for this purpose, and will be discussed later.

In practically all modern devices the pressure is applied over the artery by inflating a rubber bag fastened around the arm or leg. The bag is connected to some kind of pressure indicator of the aneroid or mercury type, which is usually graduated to indicate the pressure in the bag in terms of the height in millimeters of a mercury column (see figs. 5, 6, and 8).

It is assumed that the tissues of the arm and the walls of the artery offer no resistance to compression. The pressure of the arm bag is then considered as being directly utilized in overcoming the pressure of the blood.

Investigations have been carried out to determine what part of the pressure in the arm bag is used in actually bending the walls of the artery, buried as it is beneath the muscles, and in closing its lumen (4, 5, 6). Results have not been consistent, but the error from this cause has been variously estimated at from 2 to 10 millimeters of mercury for arteries in a healthy condition.

It is evident that from the point of view of the physician, if not the physiologist, the actual pressure existing in the artery is of little moment. Long experience of many physicians has determined that certain pressures found clinically (that is, pressures in the arm bag) are normal and others abnormal. For instance, if the physician found a blood pressure of 180 millimeters in his patient, he would recognize it as pathological and as having in that particular patient

a certain diagnostic and prognostic value. Its value in this respect would not be less if it could be shown, by connecting the artery directly to a manometer, that the intraarterial pressure was much greater or less. It is only important that any existing fundamental error in the clinical technique shall be constant. As far as this error does vary in different patients, however, it lessens the significance of any variation from what is considered normal. In arteriosclerosis, for instance, it is possible that higher readings of pressure will be found than in cases with the same intraarterial pressure but with more easily compressible arteries. Some, however, believe that vasomotor variations are more important than arteriosclerosis in introducing error (4).

To avoid, as far as possible, errors due to the pressure necessary to bend the walls of the artery, it has been shown that the arm bag should have an effective width of at least 12 centimeters for the arm of an adult and that the arm should be perfectly relaxed (7).

Some fear has been expressed that considerable error in reading may arise because the small fluctuations of pressure in the arm bag are not transmitted instantaneously to the manometer. It is true that changes of pressure are not quantitatively transmitted instantaneously in a closed system, but qualitative indications of the amount of the fluctuations are transmitted with a speed approximating that of sound from the arm bag to the manometer. When the oscillations are watched to determine the points of systolic or diastolic pressure, no errors from this source need be feared. Considering the small volume of air in the ordinary blood-testing outfit, when properly arranged, it can safely be assumed that the pressure in the manometer is equal to that in the arm bag to within a few tenths of a millimeter, a quantity which is entirely negligible in measurements of this sort.

3. TECHNIQUE OF BLOOD-PRESSURE MEASUREMENT

The pressure bag is secured loosely about the arm or leg of the subject just above the elbow or knee. Except with small children, the arm is used. Connection is made with the manometer, and air is forced into the bag until the pressure in the apparatus is raised slightly above the point where all flow of blood in the artery is stopped. The air is then allowed to escape slowly, and the gauge reading of the pressures existing in the arm bag are read on the manometer as indicated by the particular criteria used by the observer for systolic and diastolic pressures.

The pressure in the arm bag should be raised and allowed to fall as quickly as is compatible with proper care in taking observations. This precaution is necessary in order to avoid a vasomotor reaction, which may make the arterial walls less flexible, and also fatigue of the patient, which may influence the reading by causing contraction of the muscles of the arm.

It may be noticed that when the systolic or diastolic point is detected, if the leakage of the air is suddenly stopped before a reading of the manometer is taken, the mercury column or the pointer of the gauge will immediately register a pressure slightly higher by an amount depending on the volume of the system and the rate of leak before the valve was closed. The opposite effect will appear when the pressure is increasing and the system is suddenly closed. No very great error, however, is to be feared from this effect.

4. CRITERIA FOR SYSTOLIC AND DIASTOLIC PRESSURES

Three methods have been generally used for determining the systolic and diastolic pressures; that is, the external pressures which have to be applied to the arm bag—first, to maintain the artery closed except at the highest point of the arterial cycle, and second, to allow the artery to remain open except at the lowest point of the arterial cycle. These are the palpation, the oscillation, and the auscultation methods. The criteria for the systolic and diastolic pressures are by no means exactly established, and especially is this true of the diastolic pressure.

(*a*) Palpation Method.—According to the palpation method, the systolic pressure is taken as that at which the pulse at the wrist, after having been stopped by inflation of the bag, is first felt when the pressure in the arm bag is falling. The selection of this point varies greatly with the skill of the physician, since the first pulses are very weak and may occur only once in several cardiac cycles. The diastolic pressure is assumed to be equal to that in the arm bag at the time when the pulses are strongest or "throbbing." This criterion is very indefinite.

(*b*) Oscillation Method.—According to the oscillation method the two pressures are determined by noting the variations in magnitude of the pressure changes in the arm bag caused by the flow of blood in the compressed artery. These set up pressure waves in the testing system, thus causing the mercury column or the hand of the gauge to oscillate. The systolic pressure is taken as the pressure at which the first decided oscillations occur. These are caused by passage at the apex of the pressure wave of a thin stream of blood through the compressed artery, causing an abrupt change in its volume. The water-hammer effect of the blood against the wall of the artery at the point where it is closed causes oscillations at pressures far above the true systolic pressure, which must not be confused with those caused by the actual passage of blood through the artery. Ordinarily, at this point the excursion of the indicator suddenly becomes greater, but in many cases the transition is gradual, making this criterion also somewhat indefinite.

The diastolic pressure is considered by different authorities as the pressure at the first, the last, or the middle point of the series of oscillations of greatest amplitude. The basis for the assumption that the diastolic pressure is measured when the oscillations are greatest is that the change in the volume of the artery during the cardiac cycle, a measure of which is found in the fluctuation of pressure in the manometer, is greatest when the artery is completely closed by the arm bag only at the point of lowest arterial pressure; that is, at the diastolic pressure. This, however, has been seriously disputed (8).

(*c*) Auscultation Method (11).—The auscultation method is at present considered by the majority of physicians to be the most dependable. The systolic and diastolic points are determined from the different sounds made by the blood in the artery as the artery is subjected to various degrees of compression. The sounds are heard by means of a stethoscope applied just below the arm band and have been carefully described by various investigators, some observers identifying more variations and phases than others. They have been classified in eight phases, occurring as the pressure in the arm bag falls (9). These are: (*a*) Silence; (*b*) murmurs; (*c*) irregular snapping sounds; (*d*) regular rhythmic snapping sounds, growing increasingly sharper; (*e*) friction sounds; (*f*) regular rhythmic snapping sounds; (*g*) murmurs after an abrupt change from (*f*); and (*h*) silence.

The first of (*d*) and the first of (*g*) are usually taken as indications of the systolic and diastolic pressures, respectively.

Numerous theories have been advanced in the attempt to explain the cause of sound production as the compressed artery opens and closes. Thus it is claimed that the sound is due to the sudden change in the tension of the arterial walls (13), that the compressed flesh surrounding the portion of the artery under the arm bag constitutes a resonating mass which is affected by vibrations of the arterial walls (11*b*), and that it is due to the water-hammer effect of the blood as it strikes the closed artery or spurts through the partly opened artery and strikes the stagnant blood below the bag. The last theory appears to be the most probable of those which have been advanced and has been strengthened by the work of several experimenters, notably that of Erlanger (11).

5. PERSONAL EQUATION AND OTHER ERRORS OF OBSERVATION

If the manometer used with the blood-pressure outfit gave at all times an absolutely true indication of the pressure in the arm bag, large errors due to the personal equation of the physician would still occur. The possibility of these occurring is probably greatest in the case of the palpation method. Here the detection of the first pulse

50942°—27——2

beat depends directly upon the skill of the observer, since the first pulses are very weak and irregular. It is quite possible for the attention to be so focused on the sensations in the balls of the fingers that the observer's own pulse is felt and mistaken for that of the patient. When comparing two physicians' results, it should be clearly understood whether the pressure at which the first pulse was felt or that at which the pulse was regular was chosen. Consistent recognition of the diastolic pressure by the palpatory method is very difficult.

When using the oscillation method, where a mercury column or the pointer of a gauge is observed, the physician must keep a mental image of the amplitude of the previous oscillations. For the determination of the systolic pressure he must make an instantaneous decision as to which is the first oscillation not due to the water-hammer effect, and for the diastolic pressure he must judge at which point the oscillations are greatest. The systolic pressure can be determined much more accurately than the diastolic pressure by the oscillation method (10).

The auscultation method yields more definite criteria for the systolic and diastolic pressures than do the others, but even when this method is used the point at which the pressure is read varies considerably with the habits and skill of the observer.

Considerable error necessarily arises in reading the height of the mercury column or the position of the hand of a gauge when it is falling continuously and is also oscillating. This error is greater the faster the fall of pressure. The error is increased if some separate device for magnifying or recording the oscillations must also be observed, in which case only a divided attention can be given to the manometer.

III. PRESSURE INDICATORS

Many instruments have been devised to indicate accurately the pressure in the arm bag. This pressure has been measured by the height of the mercury column that it can sustain, by the deflection of an aneroid gauge, or by the compression of a column of air confined in a closed tube by a column of mercury or some other liquid.

1. MERCURIAL MANOMETER TYPE

(*a*) Principle.—The pressure indicators of all mercurial sphygmomanometers consist, essentially, of a glass U tube partly filled with mercury. If one of the legs of the tube is connected to an arm bag under pressure and the other left open to the air, the mercury will fall on the side connected to the bag and rise on the other side, until the pressure exerted by the excess of mercury in one leg over that in the other is equal to the difference between the pressure in the bag

and atmospheric pressure. Since in blood-pressure measurements it is customary to express the pressure in terms of the height of the mercury column supported by the pressure in the bag, it is only necessary to measure the vertical distance between the two mercury levels in the tubes. For accuracy, the mercury level should be taken as the top of the meniscus, but the edge of the meniscus is frequently used in an effort to reduce the parallax errors caused by failure to have the eye at the same level as the top of the mercury column.

(b) Theory of the Vertical-Tube Liquid Manometer.—When a differential pressure is applied to a liquid manometer, the liquid level falls in the leg in which the higher pressure is applied and rises in the other leg (see fig. 1). The true pressure is always given by the difference in the levels of the two legs, and this difference in level is independent of the cross-sectional areas of the tubes and, consequently, of any variations in these areas from point to point of the tubes. So, if the zero of the scale is adjusted to the lower mercury level each time a reading is taken, it is unnecessary to calibrate the manometer, and an ordinary millimeter scale can be used. Or, if preferred, two scales can be used as shown in Figure 1, one extending up the tube in which the mercury rises, the other extending down the tube in which the mercury falls, the zeros of the two scales being adjusted to the mercury levels when there is no differential pressure applied to the manometer. The sum of the two readings is a measure of the pressure, and when, as in sphygmomanometers, the liquid used is mercury and the pressures are expressed in millimeters of mercury, then, if true millimeter scales are used, the sum of the readings of the two legs gives directly the numerical value of the pressure.

Neither of these procedures is convenient, however, and it is customary instead to use a single fixed scale in connection with the leg in which the mercury rises. Under these circumstances, in preparing the scale, it is necessary to know the ratio of the cross-sectional areas of the two legs of the manometer or, for accurate work, to calibrate the manometer; that is, to determine directly the levels in the tube to which the mercury rises for known differential pressures.

"U"-tube manometer.—Referring to Figure 1, if the differential pressure P is measured in millimeters of mercury and the heights h, h_1, and h_2 are specified in millimeters, then

$$P = h = h_1 + h_2 \tag{1}$$

Furthermore, if the cross-sectional areas A of the two legs are equal, then it can be easily shown that the distance h_1 through which the mercury rises in one leg is equal to the distance h_2 through which it falls in the other leg, for the volume of mercury which is forced out of one leg must equal the volume which flows into the other; that is,

$$V = Ah_1 = Ah_2 \tag{2a}$$

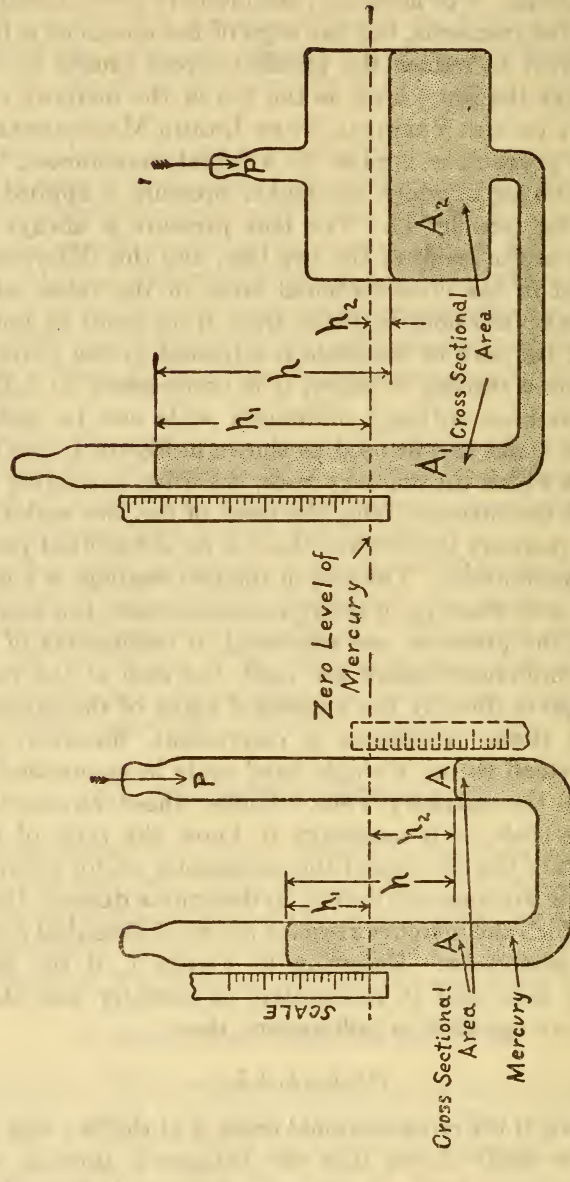

FIG. 1.—*U-tube manometer*

FIG. 2.—*Reservoir manometer*

where V is the change in volume of the mercury in each leg due to the pressure P, from which it is evident that

$$h_1 = h_2 \tag{3a}$$

when the areas of the two legs are the same.

The actual distance h_1 through which the mercury rises, measured on the scale, can now be computed by substituting equation (3a) in equation (1):

$$h = 2h_1 \tag{4a}$$

or

$$h_1 = \tfrac{1}{2}h \tag{5a}$$

That is, for a pressure of 100 millimeters of mercury, the mercury level rises 50 millimeters in the tube to which the scale is attached. Therefore, the distance between the zero and the 100 millimeter divisions on the scale is only 50 millimeters, and the graduations must be spaced only half as far apart as on an ordinary millimeter scale. This has the disadvantage of compressing the scale and thus increasing the magnitude of the errors made in reading it.

Reservoir manometer.—In order to obtain more widely spaced graduations, reservoir manometers (see fig. 2) are frequently used in place of the simple U-tube type. In the reservoir manometer the cross-sectional area of one leg is made much larger than that of the leg against which the scale is placed. Then the rise h_1 of the mercury column in the leg of small diameter is much greater than the fall of the mercury level in the reservoir.

As before,

$$P = h = h_1 + h_2 \tag{1}$$

$$V = A_1 h_1 = A_2 h_2 \tag{2b}$$

In this case, however, since A_1 is not equal to A_2

$$h_2 = \frac{A_1}{A_2} h_1 \tag{3b}$$

and

$$h = \left(1 + \frac{A_1}{A_2}\right) h_1 \tag{4b}$$

or

$$h_1 = \frac{A_2}{A_1 + A_2} h \tag{5b}$$

Assume that the cross-sectional area A_2 of the reservoir is 19 times that of the tube A_1. Now, if a differential pressure of 100 millimeters of mercury is applied to the manometer, equation (5b) shows that the mercury level in the tube will rise

$$h_1 = \frac{19}{1+19} \times 100 = 95 \text{ millimeters}$$

in the tube and so will fall 5 millimeters in the reservoir. Hence, the distance between the zero and the 100 millimeter graduations on the scale will actually measure 95 millimeters, and the graduations will, therefore, be spaced $\frac{19}{20}$ as far apart as on an ordinary millimeter scale.

(c) NECESSITY FOR CALIBRATION.—If the cross-sectional area of the two legs of a U-tube manometer or of the tube and reservoir of a reservoir manometer did not vary in any given instrument, it would be necessary only to measure these areas accurately at one cross section to compute the distance between successive graduations on the scale and to prepare the scale accordingly. Unfortunately, it is not possible to obtain glass tubing having a sufficiently uniform bore to make this procedure possible when accurate work is required. The small variations which actually occur cause the ratio

$$\frac{A_2}{A_1} \text{ or } \frac{A_2}{A_1+A_2}$$

of the manometer to vary, and therefore the successive small rises Δh_1 of the mercury column for successive pressure increments Δh or ΔP vary, as can be seen from equation (5b) if we replace h_1 by Δh_1 and h by Δh.

$$\Delta h_1 = \frac{A_2}{A_1+A_2} \Delta h \tag{5c}$$

Let the actual conditions be exaggerated and simplified by assuming that the cross section A_2 of the reservoir is constant, but that the cross section A_1 of the tube varies, being constant and equal to $\frac{1}{19}A_2$ from the 0 to the 10 millimeter divisions of the scale, constant and equal to $\frac{1}{21}A_2$ from the 10 to the 20 millimeter divisions, etc. Considering the portion of the tube from the 0 to the 10 millimeter divisions, equation (5c) gives

$$h_1 = \left(\frac{19}{1+19}\right) 10 = 9\tfrac{1}{2} \text{ millimeters}$$

as the distance which the mercury level rises for a differential pressure of 10 millimeters of mercury; that is, the distance between the 0 and 10 millimeter graduations should be 9½ millimeters.

From the 10 to the 20 millimeter graduation equation (5c) gives

$$h_1 = \left(\frac{21}{21+1}\right) 10 = 9\tfrac{6}{11} \text{ millimeters}$$

as the distance between the 10 and 20 millimeter graduations on the scale; that is, decreasing the bore of the tube with respect to that of the reservoir increases the rise of the mercury level in the tube for a given differential pressure.

(d) DESCRIPTION OF MERCURIAL SPHYGMOMANOMETERS.—Figure 3 shows a group of mercurial sphygmomanometers of the portable

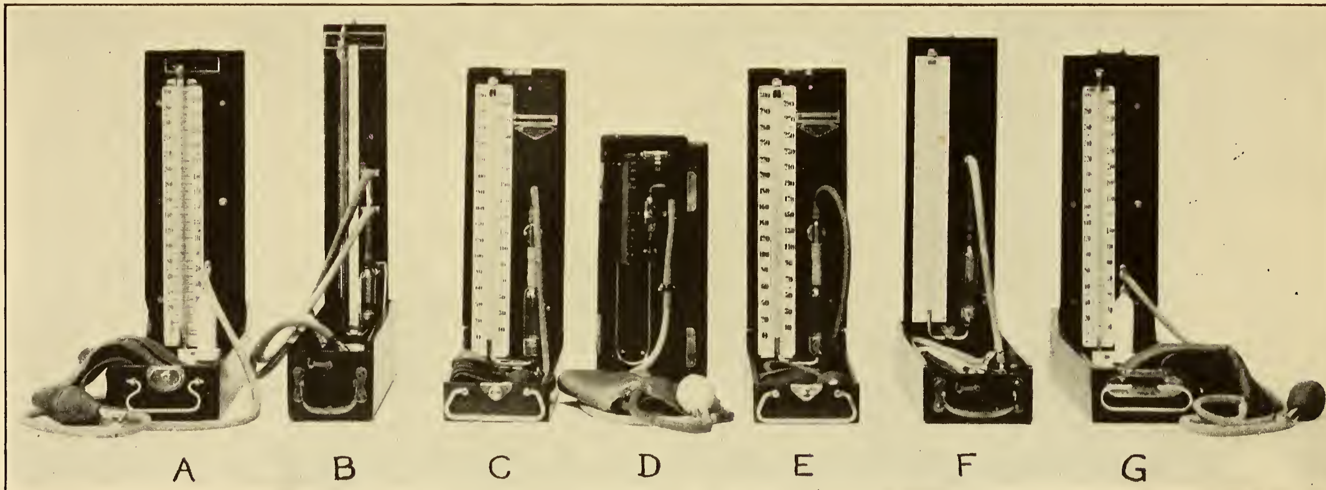

Fig. 3.—*Group of mercurial sphygmomanometers*

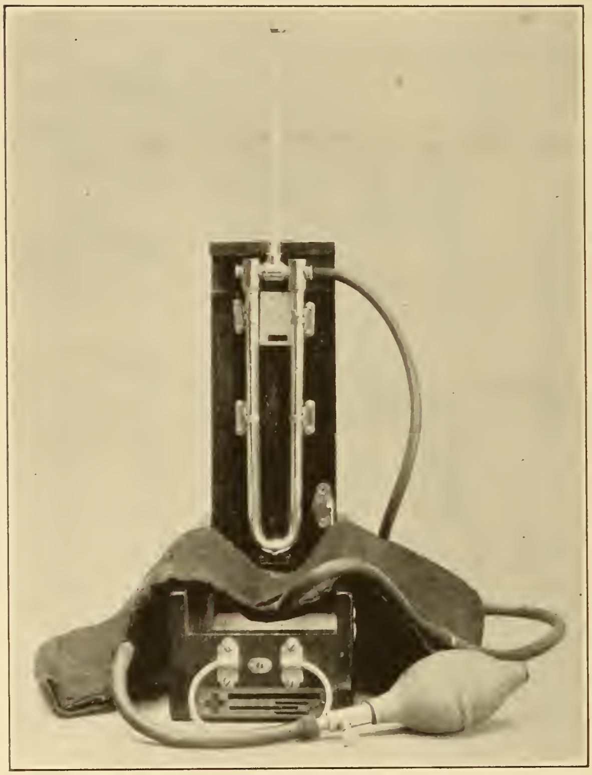

FIG. 4.—*Mercurial sphygmomanometer with folding U-tube manometer*

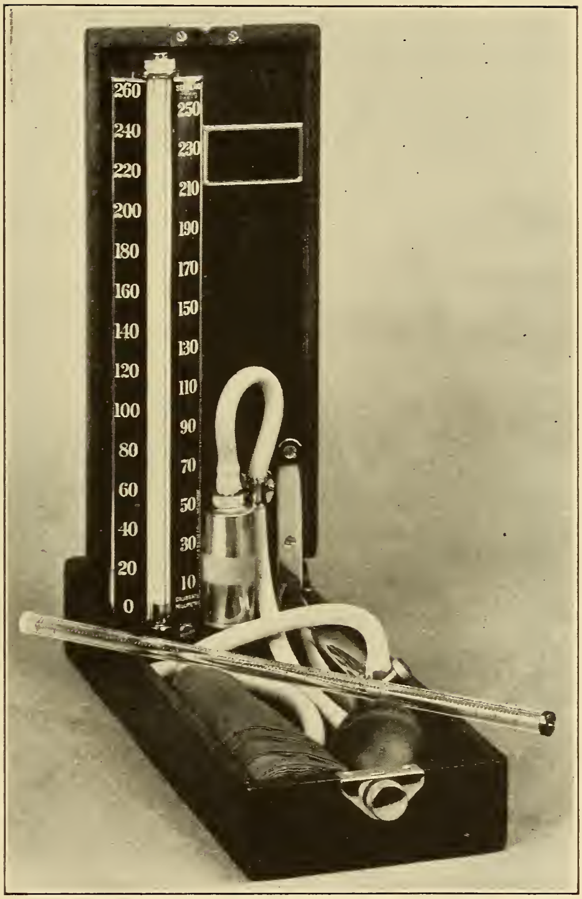

FIG. 5.—*Mercurial sphygmomanometer, pocket model, reservoir type*

Glass tube is detachable and can be replaced without the necessity of sending the instrument to factory

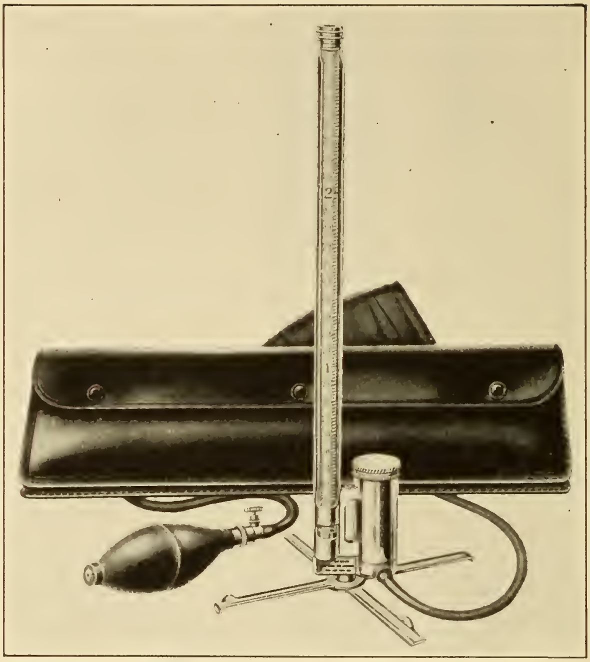

FIG. 6.—*Mercurial sphygmomanometer, reservoir type*

Glass tube is detachable and can be replaced without the necessity of sending the instrument to factory

type. All but the instrument D in the center are of the reservoir type. The relative shortness of the scale of a U-tube manometer is evident from a comparison of sphygmomanometer D (highest reading 240 millimeters of mercury) with the reservoir manometers on either side of it. Instruments B and F, also C and E, are of the same make and have reservoir manometers, which are of all-glass construction, while the two instruments A and G, both of the same make, have steel reservoirs, with the glass manometer tube set rigidly in steel sockets. There are conflicting claims as to the relative merits of these two types of construction.

Figure 4 shows a mercurial U-tube manometer with a folding tube designed to reduce the size of the instrument. The lowest pressure which can be read is 50 millimeters, as the zero position of the mercury column is below the metal fittings which allow the graduated portion of the tube to be folded in.

Figures 5 and 6 show recently developed mercurial sphygmomanometers. The design of these instruments is unique in that the glass tube is removable. Since each tube is calibrated individually, a broken tube can be replaced with a new one by the user without loss of accuracy. The instrument shown in Figure 6 is a pocket model, reservoir type. The base can be detached and folded up, and the entire manometer can then be slipped into the physician's pocket. The reservoir of this instrument is made of steel.

The instrument shown in Figure 5 has a steel reservoir, the diameter of which is held accurately within close tolerances. Glass breakage is reduced to a minimum by holding the tube in a resilient mounting consisting of steel sockets faced with cork. The top socket is held in place by the tension of a spring and hence can yield under shocks, thereby protecting the tube from breakage.

(*e*) Advantages and Disadvantages of Mercurial Sphygmomanometers.—The mercury manometer, when properly made and used, is capable of measuring pressures with greater accuracy and consistency than an aneroid gauge, whose action depends on the elasticity of metal. In order that this may be the case, however, it is necessary that the tube be calibrated carefully and that the mercury and tube be kept clean. The manufacturers of the best mercurial sphygmomanometers calibrate each tube individually.

The greatest disadvantages of the mercurial sphygmomanometer are its relatively large size, its fragility, and the necessity for keeping it upright when using it. However, the development of the pocket model instrument shown in Figure 5 or 6 demonstrates that progress is being made toward reducing the size, and the instruments with the detachable tube (figs. 5 and 6) go a long way toward eliminating the troubles due to glass breakage. In one sense there is an advantage in the fragility of the mercurial sphygmomanometer, since any break-

age puts the instrument completely out of use, whereas the aneroid type of gauge can be put seriously out of adjustment without the doctor being any the wiser.

A cause of error in the indications of mercurial manometers is the variation in the capillary action of the mercury. For purposes of an instrument in which it is not necessary to attempt an accuracy greater than ½ millimeter of mercury, this may be made negligible by making the bore of the manometer tube large enough—say, 5 millimeters or more—provided the mercury and the tube are clean. However, even if they are extremely dirty, the error is not likely to exceed 2 millimeters. When the bore of the tube is as small as 1 or 2 millimeters, the errors may become excessive if the mercury and the glass are dirty.

One of the most common errors in the use of the mercury instrument is due to failure to have it in an upright position when reading it. Many physicians do not realize that, from the very nature of the instrument, its accuracy depends on the mercury column being vertical. In any other position the instrument will read too high. This requirement may be a disadvantage when the patient is in bed. However, doctors frequently place the instrument on the bed near the patient, and, if reasonable care is taken to get the gauge level, this procedure should not cause more than 2 or 3 millimeters error.

If the oscillation method of determining the systolic and diastolic pressure is used, the mercury manometer is at a disadvantage because of the great inertia of the mercury. The first oscillations near the systolic pressure are greatly damped, while for the same reason, since the mercury once in motion tends to continue oscillating without receiving much additional impulse, they may be greatly amplified near the diastolic pressure. This effect causes additional uncertainty in the detection of the first and maximum oscillations.

It is claimed by some, although there is marked disagreement on this point, that the mercurial gauge is inadequate for measuring the diastolic pressure, since the method which they advocate for determining the latter involves the lower limit of oscillation of the pointer in the aneroid gauge or the surface of the mercury in the mercurial gauge. With the oscillation method there is some experimental evidence that the diastolic pressure is slightly below the mean pressure when the oscillations are greatest and, therefore, that the lower limit of the oscillation is slightly more accurate (6). The inaccuracies inherent in any criterion for diastolic pressure hardly justify such nicety of technique, even if on a sound theoretical basis.

(*f*) Precautions in Use.—Since the column of mercury in the instrument expands very slightly with increase in temperature, and since it is always possible that mercury may be lost, the error due to any change in the zero point should always be noted before use.

To prevent mercury from spilling, the majority of sphygmomanometers are provided with a mercury trap in the reservoir and at the upper end of the manometer tube with a cap or plug [2] which, though practically impermeable to mercury, will allow air to pass freely. If a suitable plug is used, the mercury can be forced against it under a pressure considerably above the range of the instrument without causing leakage, but, if the mercury column strikes the plug a sharp blow, minute drops may be forced through. If the mercury is frequently forced against the plug, the pores become filled with minute drops of mercury, which retard the flow of air and thus cause the mercury column to act sluggishly. The pores can be cleared of mercury by removing the plug and rolling or squeezing it between the fingers. In a few instruments the porous plug is replaced by a stopcock which should be closed when the instrument is not in use. It is absolutely necessary that this stopcock be open when readings are being taken; otherwise the instrument takes on the characteristics of a compressed-air manometer, and its readings are grossly in error.

As soon as the mercury in an instrument becomes darkened by oxidation and by the accumulation of dirt, so that it sticks on the sides of the tube and does not exhibit a meniscus in falling back in the tube at the usual rate, it should be taken out and both the mercury and the glass tube carefully cleaned.

(*g*) Directions for Cleaning.—Manufacturers usually provide with each mercurial sphygmomanometer a special brush for cleaning the inside of the glass tube. Such a brush, with its stiff bristles, while very convenient for removing streaks of mercury adhering to the glass and particles of dirt, can not be expected to remove either a greasy film or the grayish-black or yellowish chemical deposit which in the course of time clouds the tube around the zero level of the mercury. It may be mentioned here that the brush used should have no sharp metal points or edges which might scratch the tube and cause an incipient crack.

One of the best ways of cleaning the tube, if there is no opaque chemical deposit on the glass, is to wash it in warm soapy water, using the brush; then rinse thoroughly in clean warm water and dry. If it is desired to hasten drying by warming the tube, care should be taken not to heat it sufficiently to make it uncomfortable to hold in the hand, as the tube may possibly chip or crack.

If a simple washing will not clean the glass, a solution of sulphuric acid and potassium bichromate (25 grams of potassium bichromate added to a solution of 200 cubic centimeters consisting of equal parts of concentrated sulphuric acid and water) should be allowed to stand in the tube for several hours. Care should be taken to prevent this solution from touching anything but the glass. Following this the tube should be rinsed out with clean water and dried.

---

[2] Usually of dogskin or kidskin.

50942°—27——3

To facilitate this drying process, it is sometimes recommended that the washing with clean water be followed by a rinsing with alcohol and that a final rinsing with ether be given. A rinsing with grain alcohol may be recommended, but denatured alcohol frequently contains substances which leave a greasy film on the glass, and ether appears to do the same thing, although to a lesser extent. Consequently, it is as well to omit the rinsings with alcohol and ether.

The best method of cleaning mercury is by distillation, but, of course, this is not ordinarily feasible. In practically all cases a cleaning in dilute nitric acid will prove entirely satisfactory if certain precautions are used. It is preferable to use approximately 1 part of nitric acid to 10 parts of water, rather than a stronger solution. Place the dilute acid in a beaker or glass tumbler and allow the mercury to fall into it in minute drops, the smaller the better. A good way of doing this is to let it filter through small holes in a piece of filter paper or force it through an ordinary piece of clean white cotton cloth. The longer the column of acid which the drops of mercury fall through, the better will be the cleaning accomplished. Now decant off as much of the acid as possible, wash the remainder away with clean water, and again cause the mercury to fall in minute drops into the dish, filled this time with clean water. The final process is to dry the mercury thoroughly, either as a whole or, better, by allowing it to fall drop by drop into a dish heated, say, to approximately the temperature of boiling water.

When the manometer tube is refilled, the new zero position of the meniscus should be observed, since a little mercury is usually lost in cleaning. More mercury should be added, if necessary, to bring the meniscus up to the zero graduation of the scale.

In handling mercury it should be remembered that the only metals with which it will not amalgamate under ordinary conditions are iron or steel and platinum. Particular care should be taken to keep it from contact with gold articles which are valued. If it does come in contact with such articles and starts to amalagamate with the gold, it should be removed immediately. The authors have found a simple means of doing this to consist in rubbing the affected surface with the sediment obtained from cans of nickel polishes. An alternate method is that of immersion in dilute nitric acid if the nature of the article is such as to permit it. As a last resort, the article may be taken to a jeweler.

2. ANEROID GAUGE TYPE

(*a*) Principle.—Aneroid sphygmomanometers operate by the stretching under pressure of one or more metal capsules. These are built up of corrugated metal disks soldered together at the edge and have an inlet through which pressure can be transmitted to the inside (see fig. 7).

Elastic errors.—This type depends on the elasticity of the metal for its indications and hence is subject to the usual errors arising from the elastic properties of metals.

A new diaphragm capsule is in a "green" or "unseasoned" condition and will not exhibit suitable elastic properties for use in a measuring instrument until it has been "aged" or "seasoned." This seasoning process will take place over a period of years in the ordinary use of the instrument, but, as this frequently causes very appreciable changes in the calibration, it is desirable to season the diaphragms more speedily by an artificial process before they are placed in an instrument. This is usually done by deflecting the capsules over their range of use a number of times—a thousand, for example—or the diaphragms may be annealed after forming, the optimum time and temperature of annealing depending on the metal or alloy used and on its condition. After this seasoning process is complete the diaphragm capsules will not undergo any appreciable permanent change in calibration if the instrument is not abused. The diaphragm capsules of the better class of aneroid sphygmomanometers are seasoned by one of the above-described processes.

Even after the diaphragm capsules are seasoned, transient elastic errors occur owing to the fact that a piece of metal acts somewhat as if it had a memory (12). Its action under stress is always modified by its past experiences. Each stress to which it is subjected leaves a change in its condition which may be considerable at first, but which tends to disappear at a decreasing rate. This change affects the performance of the diaphragm when it is again under stress. If a sphygmomanometer is subjected 100 times in quick succession to a pressure change from zero to the maximum value shown on its scale, the reading at a given pressure will be considerably different at the hundredth time from what it was at the first, although the difference between the readings on the ninety-ninth and the hundredth deflections will be much less than that between the first and the second. If the instrument is then left undisturbed in the unstressed condition for some time, it will tend to return to its original state. See in this connection the paragraph on "Seasoning" in the section on "Results of investigation of aneroid instruments."

Two of the phenomena, usually associated together, which cause considerable trouble in instruments whose operation depends on the elasticity of metal are called hysteresis and drift. Without discussing in detail the nature or causes of hysteresis, it will suffice to say that, when the pointer of the instrument is deflected with increasing pressure to any given reading and then is allowed to return to zero, the instrument will read higher for a given pressure on the return down the scale than it did on the way up. Fortunately,

since blood pressures are measured with falling pressure, it is possible to calibrate sphygmomanometers for this condition and thus reduce the errors which would occur if readings were taken with increasing pressures as well. The increase in reading when the instrument is held at the same pressure for some time is called the "drift" or "creep." The drift, as is the case with hysteresis, is of no direct practical importance in the use of sphygmomanometers, since a given pressure reading is not held for lengths of time which vary substantially from those in calibration. These two effects, hysteresis and drift, are due to failure of the instrument diaphragms to perform as perfectly elastic bodies and are related, so that if one is relatively small the other ordinarily is small also. Hence, if either the drift or the hysteresis is found to be small for a given instrument, this indicates that the diaphragms have good elastic qualities.

Description.—Sphygmomanometers of the aneroid type in general use do not vary greatly, aside from their mechanism for transmitting and multiplying the motion of the capsules to the pointer of the gauge. Several capsules fastened one above another are used. The greater the number of capsules of a given size and flexibility the greater motion they will give for a definite change in pressure.

The pressure to be measured is usually applied to the inside of the capsules, the interior of the case being open to atmospheric pressure, since then there are fewer connections to be made air-tight. The principle involved in the bending of the metal is the same whether the pressure is applied to the outside of the capsules, compressing them, or to the inside, expanding them. When the capsules are compressed, however, a point is reached beyond which no further motion can be obtained; thus the metal is guarded against the possibility of excessive strain. Almost as good a result can be obtained in the other case, however, by suitable diaphragm stops which prevent deflection beyond a certain point.

A transmission mechanism of the most common type is shown in Figure 7. A rod R fastened to a toothed sector S at T which is in mesh with the pointer pinion P is kept in contact with the top of the diaphragm capsules C. Any expansion or contraction of the capsule moves the rod and thereby operates the geared sector and pointer. A hairspring moves the pointer back when the pressure is released. An adjustment for readily changing the amplitude of motion of the pointer is usually provided by an arrangement for altering the distance of the point of attachment of the rod on the sector (T in fig. 7) from the axis of rotation of the sector. The nearer the rod is fastened to the axis of the sector the greater the arc through which the latter will turn for a given motion of the rod.

In one instrument studied all gear wheels, and even the hairspring, were eliminated. The transmission of the motion of the capsules

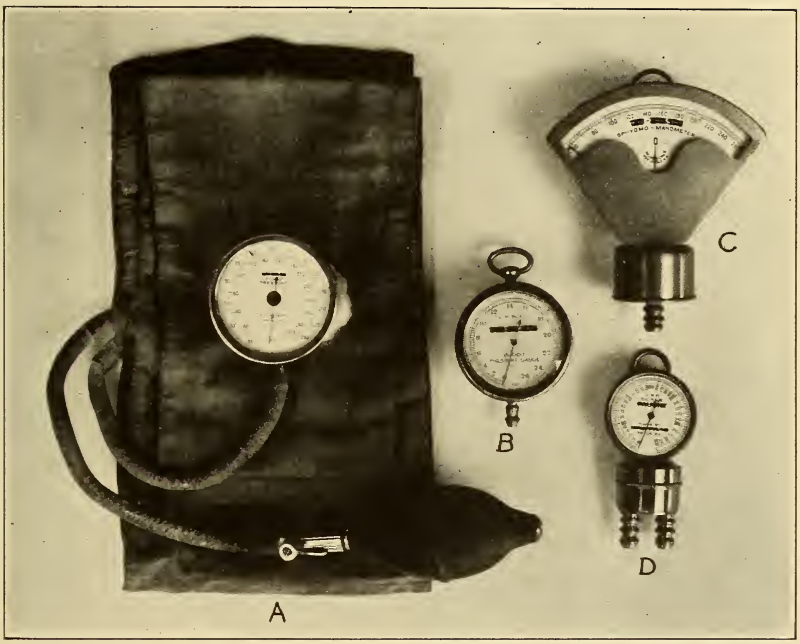

FIG. 8.—*Group of aneroid type sphygmomanometers*

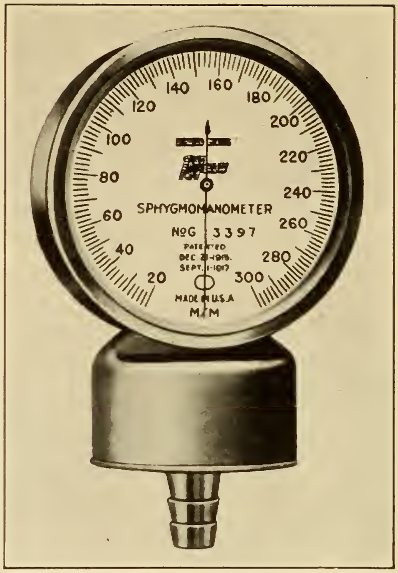

FIG. 9.—*An aneroid sphygmomanometer*

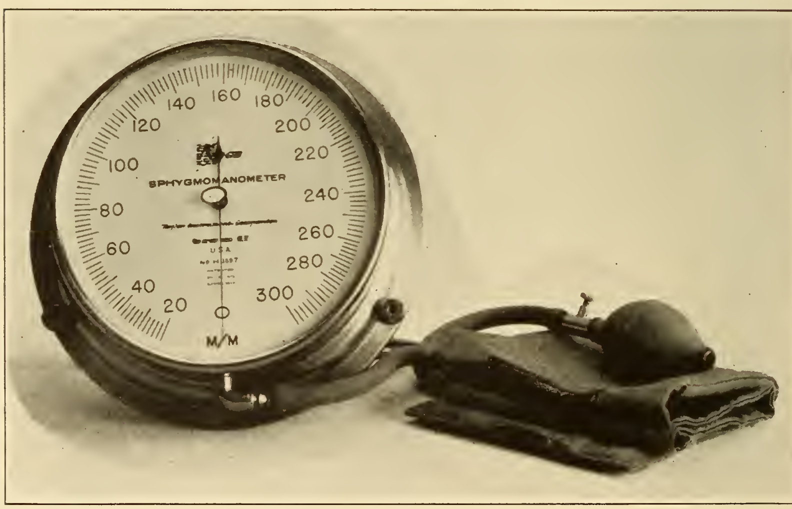

FIG. 10.—*Wall type aneroid sphygmomanometer*

was accomplished by an arrangement of weighted levers, and the force of gravity was relied upon to bring the pointer back with decreasing pressure.

Figures 8 an 9 include several different makes of aneroid sphygmomanometers. All except instrument *C* are of the general construction shown in Figure 7. Since the lowest reading of instrument *C* is 60 millimeters, an auxiliary pointer is provided to indicate the accuracy with which the diaphragm capsules return to their zero position.

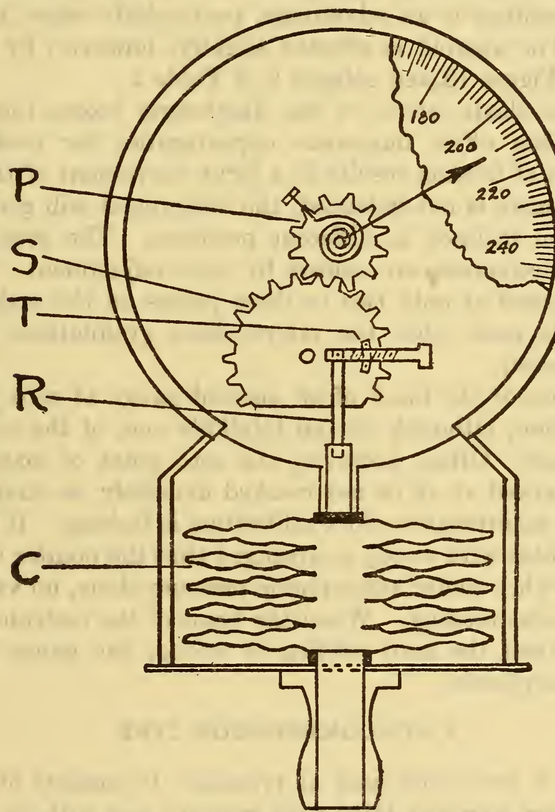

FIG. 7.—*Typical mechanism of aneroid type sphygmomanometer*

In Figure 10 is shown a large wall-type aneroid sphygmomanometer. This instrument has a large scale with large graduations and figures, so that it can be read easily from a distance.

(*b*) ADVANTAGES AND DISADVANTAGES.—Aneroid gauges are much more compact than mercury instruments and, if sturdily built, are less subject to breakage than are the latter. When the oscillation method of determining blood pressure is used, the aneroid instrument has the advantage of responding more readily to rapid fluctua-

tions of pressure than will a column of mercury, which necessarily has a relatively large inertia. The great disadvantage of any aneroid is that, since it depends for its readings on the elasticity of metal, it can not be depended on to keep its calibration indefinitely and hence must be checked occasionally against a mercurial manometer. If the diaphragms are properly seasoned, however, and the instrument is not subjected to rough handling, its reliability in this respect may be quite sufficient for practical use.

The fact that the aneroid gauge need not be in a vertical position for taking readings is an advantage, particularly when the patient is in bed. The aneroid is affected slightly, however, by tilting, as is shown by Figure 12 and column 9 of Table 2.

Besides the elastic errors of the diaphragm boxes, the transmission mechanism offers numerous opportunities for trouble. Any great amount of friction results in a jerky movement of the pointer. If the mechanism is not balanced, the instrument will give different readings when inclined in different positions. The greatest errors due to the mechanism are caused by poor adjustment. Often the gauges are tested at only two or three points on the scale, and the assumption is made that the intermediate graduations should be uniformly spaced.

The position of the hand of an aneroid gauge at zero pressure is a good criterion, although not an infallible one, of the condition of the instrument. Often, however, the zero point of instruments is either not marked at all or not marked definitely, so that even this check on the maintenance of its calibration is lacking. If the instrument is provided with a stop so arranged that the pointer will always register zero when under atmospheric pressure alone, no value can be attached to that reading. When the hand of the instrument moves jerkily, or when the zero reading is wrong, the gauge should be considered unreliable.

3. AIR-COMPRESSION TYPE

This type is not much used at present. It consists of a tube of rather fine bore partially filled with mercury and with its upper end sealed. Air is present in the bore above the mercury column. The pressure to be measured is applied in the same manner as in a simple mercury manometer, and the pressure is read from the height of the mercury column. The mercury will rise until the pressure exerted by its weight plus that exerted by the inclosed air, now under compression, is equal to the pressure to be measured. If the top of the tube is permanently sealed, the instrument is nearly worthless, since changes of temperature and barometric pressure cause it to act somewhat like a combined thermometer and barometer. In many of the instruments, however, the pressure of the air in the manometer and

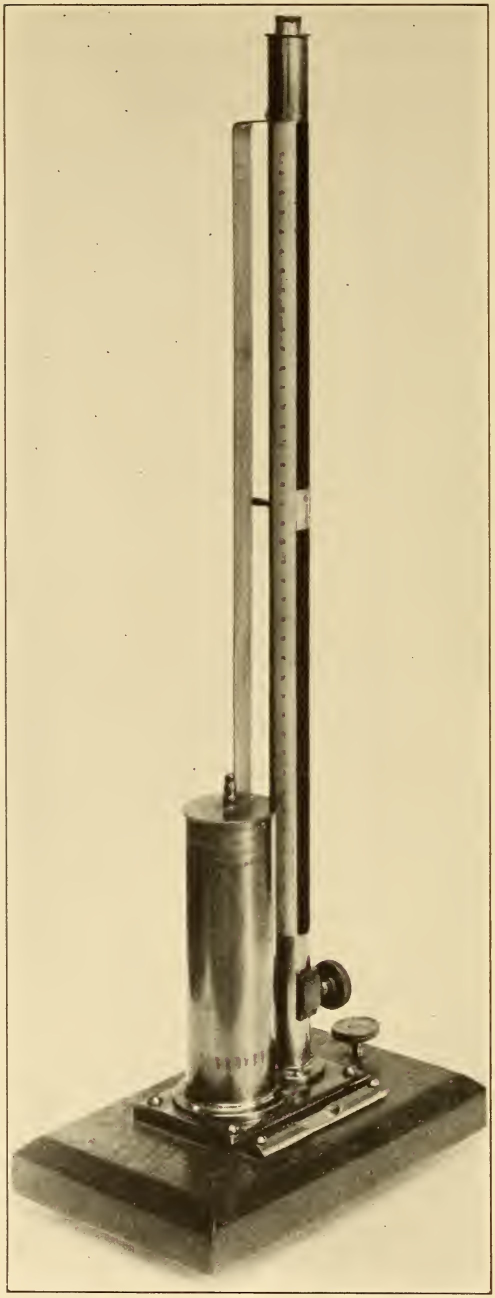

FIG. 11.—*Bureau of Standards standard manometer for use in the calibration of sphygmomanometers*

that of the atmosphere can be made the same by opening the top of the tube momentarily just before using. It must be assumed that the atmospheric pressure and the temperature of the instrument remain constant while the readings are taken.

The calibration of the air-compression type of instrument is complicated by the weight of the mercury itself, which is important here just as in any mercury manometer. In some instruments the bore of the tube is almost small enough to be called a capillary, and the erroneous assumption is made that the weight of the mercury column is negligible. Under no circumstances should the instrument be held other than perfectly upright if the gauge was originally calibrated in that position. If the temperature of the inclosed air changes during the test, another large error will be produced. Such temperature changes may easily occur if the manometer is held in the hand or even if the breath is allowed to come directly upon it.

4. RECORDING SPHYGMOMANOMETERS (2)

Recording instruments have not been included in this report, since these instruments include an additional feature, the study of which has not been completed. However, the accuracy of the measurement of pressure by a recorder should be equal to that of an indicating instrument, and therefore the tolerances given later in this report also apply to recorders. The diagnostic value of the additional data which are obtained by some recorders must be left to the physician for study and evaluation.

IV. INVESTIGATION OF PRESSURE INDICATORS

1. INSTRUMENTS STUDIED

Instruments made by nine different manufacturers were loaned to the Bureau of Standards by the makers themselves and by the United States Army Medical Corps. In all, 29 samples were received—5 mercurial and 24 aneroid instruments. They were the product of leading manufacturers of sphygmomanometers in this country and can be fairly considered as representative of the best commercial instruments available. Since the conclusion of this investigation, about 30 mercurial and 230 aneroid instruments, mostly those made by the above manufacturers, have been received and given routine tests.

2. STANDARD MANOMETER USED IN INVESTIGATION

For use in this investigation a standard manometer of some type was necessary. For this purpose a mercury manometer of the reservoir type, equipped with a vernier reading to 0.1 millimeter, was designed and constructed (see fig. 11). Tubing of large bore (8 mm)

and as uniform as possible was selected and connected to a glass reservoir, also of quite uniform diameter. The tube was constricted at the bend, so that excessive oscillations of the large mass of mercury might be avoided.

The vernier was mounted on a sleeve which could be set quickly to its approximate position and then regulated by a thumbscrew at the base of the instrument for fine adjustment. This sleeve also prevented parallax errors. A spirit level was mounted on the base and a leveling screw was provided.

The instrument was calibrated with a cathetometer against a U-tube manometer having legs of about ¾-inch bore. The tube of the instrument was marked off in four sections. The average ratio between the difference of mercury levels in the tube of the instrument and in the U tube was computed for each section, but no significant difference in that ratio was found in any of the four sections. The tube was then mounted on a dividing engine and the scale divisions engraved on it.

Careful tests made with the standard manometer indicated that, under conditions of careful laboratory use, its readings could be depended on to repeat within ½ millimeter of mercury, or slightly better. It was also found, through repeated calibrations against the U tube and against mercurial barometers of high range, that the accuracy of the readings was always within this limit, which is sufficient for the calibration of sphygmomanometers.

3. DESCRIPTION OF TESTS MADE IN INVESTIGATION

(*a*) Mercurial Manometer Type.—Each instrument was calibrated several times. Readings were taken at 30-millimeter intervals, both with increasing and with decreasing pressures; however, to maintain constant conditions, the latter readings were in all cases obtained by reducing the pressure slightly below the point to be tested and then increasing to the exact amount. The pressure was kept constant while the readings were taken. The instruments were tapped to avoid capillary errors as far as possible. Care was taken to avoid the effect of parallax.

(*b*) Aneroid Gauge Type.—*Calibration.*—Two calibrations were made in the same manner as for the mercury instruments. The readings of the manometer were taken with the pointer of the instrument exactly on each division chosen.

Effects of repetition.—The errors at the 30, 90, 150, 210, and 270 millimeter graduations were determined by three calibrations in quick succession with increasing pressures only.

Effects of seasoning.—Two calibrations were made at these same points, one before and one after 30 full-scale deflections had been

given. The instruments were rested about an hour before the second calibration was given.

Effects of friction and inclination.—Three calibrations in succession at approximately 60-millimeter intervals of the scale were made with increasing and decreasing pressure, the first with the instrument upright and without tapping, the second when the instrument was tapped before each reading, and the third with tapping when the gauge was lying on its back.

Drift.—Pressure sufficient to deflect the pointer nearly to the highest division of the scale was applied to the instrument and held constant for one-half hour, when the change in the position of the pointer was observed. The increase in reading during this time is called the drift.

Sufficient time was allowed to elapse between the different tests to insure that the instruments were in as nearly as possible the same condition for each test. Readings were taken only when the pressure throughout the testing system had become practically constant.

4. RESULTS OF INVESTIGATION

The results of this investigation are summarized in Figures 12 and 13 and in Tables 2 and 4. For purposes of comparison, the results are given separately for the mercurial and for the aneroid instruments. Furthermore, for each type of instrument the data are shown for individual manufacturers, each manufacturer being designated by an arbitrary letter.

Before the results of the tests are discussed, the significance of the arithmetic average correction and the algebraic average correction will be explained with the aid of an example. Assume that the calibration of a sphygmomanometer with pressures decreasing gave the results given in Table 1

Table 1

Instrument reading	Correction
mm mercury	*mm mercury*
300	−4.5
270	−2.5
240	−1.0
210	+1.0
180	+2.5
150	+3.5
120	+4.0
90	+2.0
60	+.5
30	+1.5
Sum of plus corrections	+15.0
Sum of minus corrections	−8.0
Arithmetic sum	23.0
Algebraic sum	+7.0
Arithmetic average corrections	2.3
Algebraic average corrections	+.7

Throughout this paper corrections are given in place of errors. The correction of the instrument for any given pressure is that quantity which, when added algebraically (that is, added when plus and subtracted when minus) to the instrument reading gives the true pressure.

The arithmetic average correction is an indication of the magnitude of the corrections which may be expected, regardless of whether the value is positive or negative. The algebraic average correction shows how well positive corrections at one part of the scale are balanced by negative corrections at another. An instrument with a large algebraic average correction can be improved simply by shifting the zero position of the pointer or by changing the level of the mercury, whereas one with a zero algebraic average correction can not be improved at all in this way.

(*a*) Aneroid Instruments.—The results for the aneroid sphygmomanometers are given in Table 2 and are plotted in Figure 12.

Table 2.—*Data for aneroid sphygmomanometers tested in investigation*

1	2	3	4	5	6	7	8	9	10
Manufacturer	Instrument No.	Arithmetic average correction	Algebraic average correction	Maximum correction	Average increment in reading due to seasoning	Effect of repetition	Effect of friction	Effect of inclination	Drift
		mm	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*
A	1	1.9	−1.9	2.5	−0.1	0.3	0.1	1.4	5.0
	2	1.4	−1.4	3.0	.0	.4	.5	1.7	2.0
	3	2.3	−2.3	4.0	−.4	.4	.4	1.2	3.0
	4	5.0	−5.0	5.5	−.5	.5	.2	1.4	4.0
	5	1.8	−.4	3.5	−.1	.7	.2	1.4	2.0
	6	2.9	−2.9	5.5	+.6	.6	.3	1.6	3.5
	7	5.1	−5.1	7.0	+.2	.4	.4	1.7	3.5
B	8	1.5	+.2	2.5	+.9	.2	.3	1.2	1.0
	9	5.4	−5.4	7.0	+1.2	.3	.4	1.2	3.0
	10	2.6	+2.6	3.5	.0	.4	1.9	2.0	2.0
	11	4.7	−4.7	5.5	+.6	.7	.6	1.5	2.5
	12	2.5	+2.5	4.0	.0	.3	.3	.6	2.0
	13	7.4	+7.4	8.5	+.3	.7	.5	3.2	3.5
	14	.4	+.2	1.0	−.1	.3	.4	1.5	3.0
C	15	4.1	−4.1	6.5	+.7	1.4	.7	3.5	6.0
	16	7.4	−7.4	11.5	+1.5	1.1	.4	2.8	4.5
	17	5.8	−5.8	9.5	+.8	.3	.8	3.2	.5
	18	2.0	−1.5	3.5	+3.1	1.0	2.0	3.6	3.5
	19	8.0	−8.0	10.5	+1.0	1.1	.6	3.5	3.5
	20	6.0	+6.0	7.5	.0	.5	.1	3.5	1.5
D	21	4.5	+3.0	6.0	+1.0	.4	.9	4.1	2.5
	22	2.1	+2.1	6.0	−.6	.3	.4	3.9	2.5
E	23	2.8	−2.8	4.5	−.2	.4	.3	1.2	.5
Average		3.8	3.6	5.6	.6	.55	.55	2.2	2.8

Calibration.—Columns 3, 4, and 5 of Table 2 and Figure 12 (*a*) show the average arithmetic, average algebraic, and maximum corrections for each instrument for readings taken with decreasing pressure only. In most cases the algebraic average correction is the same as the arithmetic average, showing that for any given instrument all of the

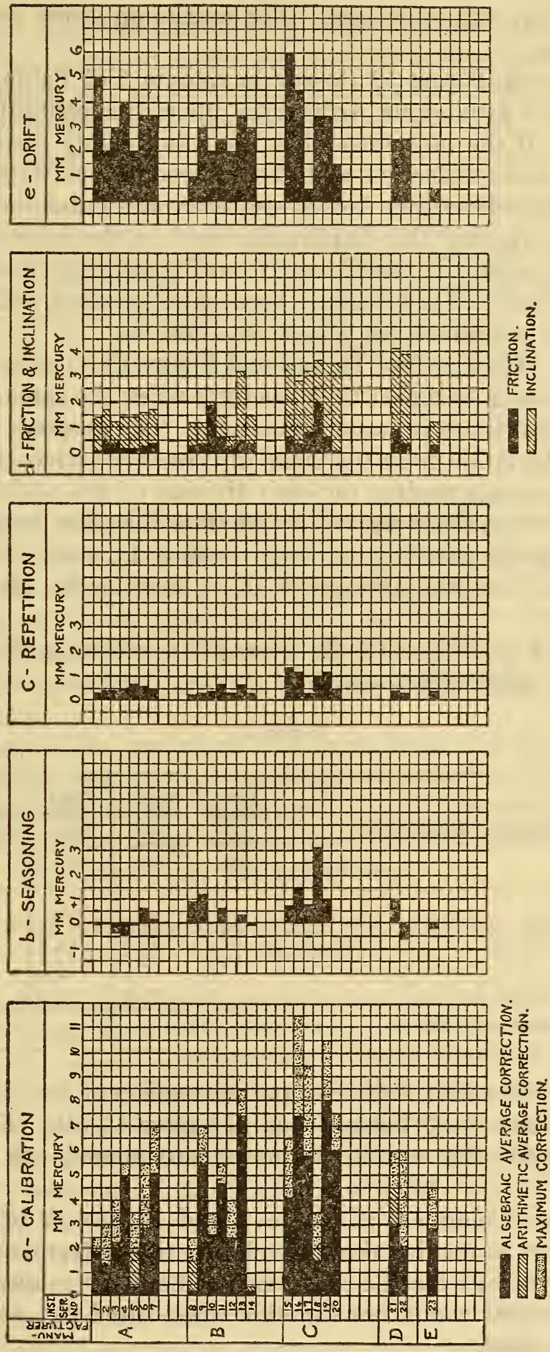

FIG. 12.—*Results of investigation of aneroid sphygmomanometers*

corrections have the same sign. The maximum errors are excessive in most cases.

Seasoning.—In Figure 12 (*b*) and in column 6 of Table 2 is shown the effect of 30 full-scale deflections upon the calibration of the instrument. If the instrument has been thoroughly rested between the last full-scale deflection and the succeeding calibration, a comparison of the calibrations before and after the full-scale deflections will indicate whether the diaphragms used in the instrument have been suitably aged. It would seem from Figure 12 (*b*) that manufacturer A had seasoned the capsules used in his product, while it seems probable that manufacturer C had not done so.

Repetition.—Column 7 of Table 2 and Figure 12 (*c*) show the ability of the instruments to repeat their readings when the same instrument is tested several times in rapid succession. The diagram is based on the average deviation from the mean of three successive calibrations; that is, the average reading for each division on the scale which was a multiple of 60 millimeters was found from the three tests, then the average deviation from this average reading for each of the points was computed and the average of the quantities for all the points taken.

The method of computing the average deviations is illustrated by the following hypothetical data:

TABLE 3

Instrument reading in millimeters	First calibration correction	Second calibration correction	Third calibration correction	Average correction	Average deviation for one reading
	mm	*mm*	*mm*	*mm*	*mm*
300	+3.0	+3.0	+2.5	+2.8	0.2
240	+2.5	+2.5	+2.5	+2.5	.0
180	+2.0	+2.0	+1.5	+1.8	.2
120	.0	−.5	−.5	−.3	.2
60	.0	−1.0	−1.0	−.7	.4
Average deviation for instrument					.2

Friction.—The effect of friction on the reading of the instrument is shown in column 8 of Table 2 and in Figure 12 (*d*). The average friction error for any well-made instrument should not exceed 0.5 millimeter.

Inclination.—Column 9 of Table 2 and Figure 12 (*d*) show the average change in reading due to inclining the instrument backward through 90°, except for the instruments made by manufacturer B. These instruments would not function when tilted 90°, so they were tipped 45° instead.

Drift.—Column 10 of Table 2 and Figure 12 (*e*) show the drift exhibited by these sphygmomanometers in one-half hour. This

effect is not important in blood-pressure gauges, since the pressure is not applied for more than a few minutes at one time.

(b) MERCURIAL INSTRUMENTS.—The data for the five mercurial instruments tested in the investigation are given in Table 4 and are plotted in Figure 13.

TABLE 4.—*Data for mercurial sphygmomanometers tested in investigation*

Manufacturer	Instrument No.	Arithmetic average correction	Algebraic average correction	Maximum correction
		mm	*mm*	*mm*
F	24	0.9	−0.9	2.0
	25	1.3	−1.3	2.5
G	26	1.0	+.5	2.5
H	27	1.4	−1.4	2.0
J	29	2.8	−2.8	
Average		1.5	1.40	2.25

Calibration.—It will be observed that the algebraic, arithmetic, and average corrections are about half the corresponding corrections of the aneroid instruments. In most instances the algebraic and arithmetic errors are equal for a given instrument, showing that the errors are either all negative or all positive. This is probably due to errors in the standards used by the manufacturers for calibrating the manometers.

Hysteresis.—The hysteresis due to sticking of the mercury is not shown; but it was small, averaging less than ½ millimeter for the individual instruments. Instrument No. 27 had a tube whose internal diameter was fairly large—about ¼ inch. The hysteresis exhibited by this instrument was negligible.

5. DATA FOR SPHYGMOMANOMETERS TESTED SINCE INVESTIGATION

(a) ANEROID SPHYGMOMANOMETERS.—Table 5 includes the arithmetical average, the algebraic average, and the maximum corrections for 80 of the aneroid sphygmomanometers tested at the Bureau of Standards during approximately the last two years.[3] In general, these instruments should show better performance than the group tested in the investigation (see Table 2), since the instruments listed in Table 5 were new in most instances, while the instruments tested earlier were probably several years old at the time of the investigation. The letters used to designate the various manufacturers have been made consistent with Table 2; that is, "manufacturer A" in Tables 2 and 5 refers to the same firm and to the same type of instrument. Asterisks have been used to designate those instruments which failed

[3] There were actually about 230 aneroid instruments tested during this period, but the number listed is sufficient to provide characteristic data.

to meet the tolerances specified by the Bureau of Standards. In a number of instances an instrument number is marked with an asterisk, but no data are given. In such cases the instrument failed to function at all and so was rejected. The instrument is included in the list, however, in order to show what proportion of the instruments

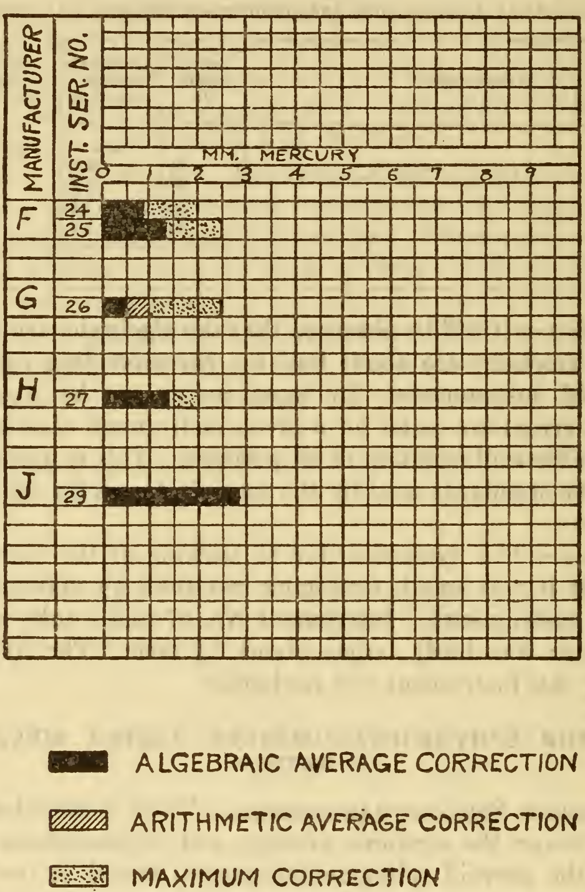

FIG. 13.—*Results of investigation of mercurial sphygmomanometers*

submitted have been rejected. A few cases occur in Table 5 in which the maximum error for an approved instrument exceeds the tolerance of 3 millimeters. This is due to the fact that a sphygmomanometer which shows good performance, except for an error exceeding the tolerance at the top of the scale, usually is not rejected.

TABLE 5.—*Data for aneroid sphygmomanometers tested since investigation*

Manufacturer	Instrument No.	Arithmetic average correction	Algebraic average correction	Maximum correction	Manufacturer	Instrument No.	Arithmetic average correction	Algebraic average correction	Maximum correction
		mm	*mm*	*mm*			*mm*	*mm*	*mm*
A	121	2.0	−2.0	4.0	A	222	0.3	−0.1	1.0
	132	1.8	+1.8	2.0		223	1.0	+.6	2.0
	136	1.8	−1.6	2.5		224	.4	+.4	1.0
	137	1.0	−1.0	2.0		227-A	.8	.0	4.0
	138	.8	+.1	2.5		280	.4	−.4	2.0
B	*124	2.8	+2.8	8.0	B	171	1.7	+1.5	3.0
	139	1.2	+1.0	2.0		172	1.2	+1.2	3.0
	140	1.9	−1.5	4.0		*173	3.2	+3.2	5.0
	*141	3.3	−3.3	5.0		174	.7	+.7	2.0
	142	1.3	−1.3	3.0		175	1.0	−1.0	2.0
	143	.4	+.2	2.0		176	1.0	+.2	2.0
	144	.5	−.3	2.0		*177	2.7	+2.7	4.0
	145	1.9	+1.9	3.0		178	1.2	+.2	2.0
	146	.6	−.6	2.0		179	1.3	+.9	3.0
	147	2.1	−2.1	2.0		180	1.6	−1.6	3.0
	148	.9	−.9	3.0		*181	------	------	------
	149	1.3	+.3	2.0		182	.7	+.7	2.0
	*150	2.3	+2.3	4.0		183	.6	+.2	2.0
	151	.7	+.3	2.0		*184	2.8	+2.8	4.0
	*152	------	------	------		*185	------	------	------
	153	.6	+.6	2.0		186	1.2	−1.0	3.0
	154	1.5	+1.5	3.0		187	.8	−.8	2.0
	*155	3.9	+3.7	6.0		*188	2.9	+2.9	5.0
	156	.7	−.1	2.0		*189	2.0	+2.0	4.0
	157	2.4	+2.4	3.0		*190	2.4	+2.4	4.0
	158	.2	.0	1.0		191	1.0	+.4	2.0
	*159	2.7	+2.7	5.0		192	.4	+.2	1.0
	160	1.8	+1.8	3.0		193	1.6	+1.6	2.0
	*161	3.5	+3.1	6.0		*194	2.2	−2.0	5.0
	*162	2.6	+.8	5.0		*195	3.7	+3.7	6.0
	*163	------	------	------		196	.7	+.7	2.0
	164	.8	−.2	2.0		197	.6	−.2	2.0
	165	.8	+.2	2.0		*198	2.0	+.8	5.0
	166	1.5	+1.3	3.0		199	1.4	+.6	2.0
	167	1.0	+.8	2.0		*200	2.8	+2.8	4.0
	*168	------	------	------		201	.3	+.3	1.0
	*169	3.8	+3.8	5.0		202	1.7	−1.7	3.0
	170	1.1	+1.1	2.0		203	.9	−.9	3.0
C	*125	3.2	−3.0	6.0					
D	*122	4.2	−3.5	7.5					
	*123	14.7	−14.7	19.0					
K	*126	2.6	−2.4	4.0					

(*b*) MERCURIAL SPHYGMOMANOMETERS.—Table 6 includes the arithmetical average, the algebraic average, and the maximum corrections for 30 mercurial sphygmomanometers tested during the past three years.

TABLE 6.—*Data for mercurial sphygmomanometers tested since investigation*

Manufacturer	Instrument No.	Arithmetic average correction	Algebraic average correction	Maximum correction	Manufacturer	Instrument No.	Arithmetic average correction	Algebraic average correction	Maximum correction
		mm	*mm*	*mm*			*mm*	*mm*	*mm*
F	130	0.8	+0.8	1.5	L	127	0.4	−0.4	1.0
	131	.6	+.2	1.5		231	.2	−.2	.5
	228	.9	+.9	2.5		275	.5	−.5	1.0
	229	.6	+.6	2.0		278	.1	−.1	1.0
	276	.8	+.6	2.0					
						285	.2	+.1	.5
	280	.3	−.3	1.0		289	.4	.0	1.0
	286	.6	+.6	1.5		290	.2	+.2	.5
	287	.4	+.4	1.0		291	.9	−.9	1.0
	288	.2	+.0	1.0					
					M	128	.2	−.2	1.5
H	129	.4	+.1	1.0		*134	3.1	−3.0	5.0
	227	1.0	−1.0	1.5		225	2.0	−2.0	3.0
	282	.8	−.8	1.5		226	1.6	−1.6	3.0
						*230	3.6	−3.6	5.0
	281	.6	−.6	1.5		*279	2.9	−2.9	11.0
	284–B	.6	−.6	1.5					
	292	1.4	−1.4	2.0	N	232	.9	−.4	1.5

(*c*) DISCUSSION OF ALL DATA.—The data in Tables 2, 4, 5, and 6 are summarized in Tables 7 and 8. The data given in the above tables are averaged for each manufacturer.

TABLE 7.—*Summary of results for instruments tested in investigation*

ANEROID TYPE

Manufacturer	Number of instruments tested	Average arithmetic correction	Average algebraic correction[1]	Maximum correction	Seasoning	Repetition	Friction	Inclination	Drift
		mm	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*
A	7	2.9	2.7	4.4	0.3	0.5	0.3	1.5	3.3
B	7	3.5	3.3	4.6	.4	.4	.5	1.6	2.4
C	6	5.6	5.5	8.2	1.2	.9	.8	3.3	3.3
D	2	3.3	2.5	6.0	.8	.3	.6	4.0	2.5
E	1	2.8	2.8	4.5	.2	.4	.3	1.2	.5
Average of all 23 instruments	--------	3.8	3.6	5.6	.6	.55	.55	2.2	2.8

MERCURIAL TYPE

Manufacturer	Number of instruments tested	Average arithmetic correction	Average algebraic correction[1]	Maximum correction
		mm	*mm*	*mm*
F	2	1.1	1.1	2.2
G	1	1.0	.5	2.5
H	1	1.4	1.4	2.0
J	1	2.8	2.8	--------
Average of all 5 instruments	--------	1.5	1.4	2.2

[1] In the above table the "Average algebraic correction" is obtained by taking the average of the values of the algebraic average corrections for each instrument, ignoring the sign of the correction.

Instruments tested since investigation

ANEROID TYPE

Manufacturer	Number of instruments tested	Average arithmetic correction	Average algebraic correction	Average of maximum correction
		mm	*mm*	*mm*
A	10	1.0	0.8	2.3
B	66	1.6	1.4	3.1
C	1	3.2	3.0	6.0
D	2	9.4	9.1	13.2
K	1	2.6	2.4	4.0
Average of all 80 instruments		1.8	1.6	3.3

MERCURIAL TYPE

Manufacturer	Number of instruments tested	Average arithmetic correction	Average algebraic correction	Average of maximum correction
F	9	0.6	0.5	1.6
H	6	.8	.8	1.5
L	8	.4	.3	.8
M	6	2.2	2.2	4.7
N	1	.9	.4	1.5
Average of all 30 instruments		.9	.8	2.0

TABLE 8.—*Proportion of instruments rejected—Instruments tested since investigation*

ANEROID TYPE

Manufacturer	Number of instruments tested	Number of instruments rejected	Percentage rejected
A	10	0	0
B	66	23	35
C	1	1	100
D	2	2	100
K	1	1	100
Total	80	27	34

MERCURIAL TYPE

Manufacturer	Number of instruments tested	Number of instruments rejected	Percentage rejected
F	9	0	0
H	6	0	0
L	8	0	0
M	6	3	50
N	1	0	0
Total	30	3	10

Tables 7 and 8 show that the mercurial sphygmomanometers as a class are considerably more accurate than the aneroids. The more recent instruments of both types are distinctly better than the earlier ones tested. With respect to the aneroid instruments, this may be partly due to the fact already mentioned, that the instruments tested in the investigation were several years old when tested, while the more recent instruments were in many cases new. This is not true of the mercurial instruments tested, however, hence it is obvious that there has been an increase in the accuracy of the mercurial instruments during the past few years.

The effect of a dirty tube and dirty mercury was very clearly brought out by tests on instrument No. 231, manufacturer L. The tube and mercury were so slightly contaminated that the fact was not

evident to the eye, but it was noticed during the calibration that the mercury was sticking to the front of the tube and causing errors which were larger than usually found for an instrument made by this manufacturer. The calibration was completed, the tube was cleaned and filled with distilled mercury, and the calibration was repeated. The data for the two calibrations are given in Table 9.

TABLE 9

Instrument	Arithmetic average correction	Algebraic average correction	Maximum correction	Remarks
	mm	*mm*	*mm*	
231	1.70	−1.70	2.0	Tube and mercury slightly dirty.
231	.25	−.25	.5	Tube and mercury clean.

The instrument met the Bureau of Standards tolerances in both tests, but its perfromance was only fair in the first test, while it was excellent in the second. It is probable that, if the tube and mercury had been extremely dirty, the error would have been no greater than it proved to be when they were only slightly dirty.

6. STANDARD TESTS

The uncertainties in the fundamental theory of blood-pressure measurements are of little concern to the physician as a clinician. It suffices if a method is available with which consistent data can be obtained by all clinicians. The divergence of opinion regarding the criteria for determining the pressure by this method, the magnitude of the personal factor of the observer in his judgment of systolic and diastolic points, and the actual errors of observation in reading the manometer evidently greatly limit the accuracy which at present can be obtained. Nevertheless, outside sources of error do not excuse preventable errors in the instrument, and no great advance can be made in the use of blood-pressure measurement to detect and diagnose pathological conditions if accurate instruments are not available.

At the request of this bureau, a number of physicians and instrument manufacturers suggested what they considered suitable tolerances. The average of the tolerances suggested by the manufacturers was 3.0 millimeters; the average suggested by physicians, all but four of whom are members of the faculties of medical schools, was approximately 4.4 millimeters. The smallest tolerance suggested was from 1 to 2 millimeters, the largest was from 5 to 10. Little distinction was made between the tolerances for mercury and for aneroid instruments.

The choice of standard tolerances must be influenced to a certain extent by the precision which can be obtained without excessive difficulty by the manufacturer. Consequently, the attempt has been made to specify tolerances which, on the one hand, can be met by a

good instrument without involving unnecessarily high cost of manufacture and which, on the other hand, are consistent with the recommendations made by physicians and physiologists.

Careful consideration has been given to the question of establishing two sets of tolerances—one for aneroid gauges and one for mercurials. However, it is undersirable to have two sets of tolerances for the instruments, since both types are to be used for the same purpose. Furthermore, if as rigid a tolerance is established as that suggested by physicians and one which at the same time even the manufacturers of aneroids admit they should meet, it seems fair to use these tolerances for both types of instruments, since the mercurial instruments can easily meet tolerances which are fair for aneroid gauges. Certificates which are issued by the Bureau of Standards contain the actual calibration of the instrument, instead of stating simply that the gauge performs within the tolerances set by this bureau. This will enable any physician who requires greater accuracy than is provided for by these tolerances to select a gauge whose calibration is shown by its certificate to be particularly good. Mercurial blood-pressure gauges having no error greater than one-half millimeter at any point of the scale have been tested at the Bureau of Standards, so that it is definitely known that instruments which meet the most rigid requirements suggested to this bureau can be produced commercially.

The following tests and tolerances were adopted as a result of this investigation. The tests are designed to detect quickly and simply any characteristics of a gauge which would make it unreliable in actual use without attempting to differentiate between the causes of any errors found.

(*a*) Tests for Mercurial Sphygmomanometers.—One calibration is made without tapping and with decreasing pressure only. Readings are taken in succession at the highest point of the scale and at all other points which are multiples of 30 millimeters. The readings are taken with the pressure falling at a rate of approximately one-half millimeter per second, which is approximately in accordance with the actual use of the instruments.

(*b*) Tests for Aneroid Sphygmomanometers.—*Complete test.*—Three calibration tests are made without tapping and with decreasing pressure only. The readings are taken with the pressure falling at a rate of approximately one-half millimeter per second. The first calibration is made only after at least 24 hours have elapsed since the last application of pressure to the instrument. Readings are taken with decreasing pressure at the highest point of the scale and at all other points which are multiples of 30 millimeters. The hand of the instrument is brought to an even division and the pressure read on the manometer. The second calibration is run not less than six hours afterwards in the same manner, except that the gauge is inclined

backward at an angle of 45°. Between the second and third calibrations the instrument is given 30 full-scale deflections. It is then allowed to rest for 24 hours, and at the end of that time it is calibrated as in the first test.

These tests are to be made without tapping and with falling pressure, since this reproduces the conditions of use. The first calibration is a test of the instrument under the conditions which exist in perhaps the great majority of cases; that is, where it is used a few times a day with intervals of rest. The second calibration takes account of the fact that the gauge is often inclined considerably when attached to a patient's arm. The third test is a measure of the ability of an instrument to retain its calibration. By allowing the instrument to rest 24 hours for the temporary elastic effects to disappear, and then recalibrating, any permanent change which may have taken place in the diaphragms can be detected. This is done by comparing the third calibration with the first.

Short test.—This is merely the first calibration test described in the second preceding paragraph. The short test is frequently substituted for the complete test when the instrument under test is the product of a manufacturer whose instruments are uniform and of good quality.

7. TOLERANCES

The error at any point in any of the tests for either type of instrument shall not exceed 3 millimeters. The difference of pressure necessary to move the pointer or the mercury meniscus through any 30-millimeter interval must not be less than 27 nor more than 33 millimeters of mercury. Excessively irregular motion of the pointer or excessive sticking of the mercury column shall be considered a sufficient cause for the rejection of the instrument.

The tolerances which have been specified above as a result of this investigation of sphygmomanometers are used as a criterion of the quality of blood-pressure instruments submitted to the Bureau of Standards for test. They are fair to the manufacturer, who should be able to make instruments which will perform within these limits, and sufficiently rigid for the ordinary use of the physician or the physiologist. Since the actual calibration of each instrument tested is submitted with the certificate, an instrument adapted to more rigid requirements can readily be selected for special use

8. CERTIFICATES

The Bureau of Standards issues a certificate for a sphygmomanometer when the instrument has a performance equal to or within that specified in this paper under "Tolerances." The certificate may also be taken as an indication that the pressure indicator is free from serious defects in design and workmanship.

If an instrument is not eligible for a certificate, a report giving the results of test will be issued. This report will include a statement of the reasons for refusing a certificate. If the instrument is usable, a statement will be included in the report giving the accuracy which may be obtained when the corrections given in the report are applied

Form 1a HBH:SBB
11—30 VI-3/Tna-48369 DEPARTMENT OF COMMERCE

Bureau of Standards

Certificate

FOR

Mercurial Sphygmomanometer
B.S.Ser.No.405 Ident.No.14356

Maker: A.B.C.Co. B. S. No. 210

SUBMITTED BY

A.B.C. Co.

The above-described mercurial sphygmomanometer was calibrated against a standard mercurial manometer in the manner specified by the Bureau of Standards in Aeronautic Instruments Circular No. 51, "Sphygmomanometers". The test was made with the mercury falling at the rate of about 0.5 millimeter per second. The instrument was not vibrated during the tests.

The corrections are given in the following table and are to be added algebraically (i.e. added when + and subtracted when -) to the instrument reading in order to give the true pressure

Instrument Reading (mm mercury)	Corrections (mm mercury)
300	-0.5
270	0.0
240	+0.5
210	+0.5
180	-0.5
150	-1.0
120	-1.0
90	-1.0
60	-1.0
30	-0.5
0	0.0

The corrections for this sphygmomanometer are within the tolerances specified by the Bureau of Standards.

George K. Burgess, Director.
LJB

Washington, D.C.
February 1, 1927.

Fig. 14.—*Typical certificate for a sphygmomanometer*

to the readings. A report may therefore serve, if corrections are applied to the readings, to enable the user to secure satisfactory and reliable measurements.

Figure 14 shows a certificate for a mercurial sphygmomanometer. Certificates for aneroid barometers will contain the corrections for

each of the three calibration tests specified for the complete test in the section on "Tests." No certificate will be given for an aneroid instrument on the basis of the short test. A change will be made in certificates after this paper is issued in that a reference to this paper will be substituted for that to Aeronautic Instruments Circular No. 51.

V. REFERENCES

1. The Clinical Study of Blood Pressure, T. C. Janeway, D. Appleton & Co.; 1904.
2. Blood Pressure and its Clinical Applications, G. W. Norris, Lea & Febiger; 1916.
3. Blood-pressure measurements, E. S. Kilgore, Lancet, **2**, p. 236; August 24, 1918.
4. An experimental study of the resistance to compression of the arterial wall, T. C. Janeway and E. A. Park, Archives of Internal Medicine, p. 586; November, 1910.
5. Some sources of error in blood-pressure measurements, E. S. Kilgore, Colorado State J.; March, 1914.
6. On the method of measuring the systolic pressure in man and the accuracy of this method, L. Hill and M. Flock, British Medical J., **1**, p. 272; 1909.
7. A new instrument for determining the minimum and maximum blood pressure in man, J. Erlanger, Johns Hopkins Hospital Reports, **12**, p. 53; 1904.
8. Physical mechanisms in blood-pressure measurement, C. Brooks and A. B. Luckhardt, American Journal of Physiology, **40**, No. 1; March, 1916.
9. Sounds heard in auditory method of measuring the blood pressure, C. Brooks and A. M. Bleile, J. Am. Medical Assn., **71**, p. 514; August 17, 1918.
10. The large personal factor in blood-pressure determination of the oscillatory method, E. S. Kilgore, Archives of Internal Medicine, **16**, pp. 873–916; December, 1915.
11. Studies in Blood Pressure Estimation by Indirect Methods.
    J. Erlanger: (*a*) The mechanism of the oscillatory criteria, Am. J. of Physiology, **39**, p. 401; 1916. (*b*) The mechanism of the compression sounds of Korotkoff, Am. J. of Physiology, **40**, p. 82; 1916.
12. Diaphragms for Aeronautic Instruments, M. D. Hersey, United States National Advisory Committee for Aeronautics Technical Report No. 165; 1923.
13. Blood Pressure in Ocular Work, E. G. Wiseman, John P. Smith Printing Co., Rochester, N. Y.; 1916.

WASHINGTON, April 20, 1927.

INDEX TO VOLUME 21

O